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(54) Title: BEARING CONDITION EVALUATION
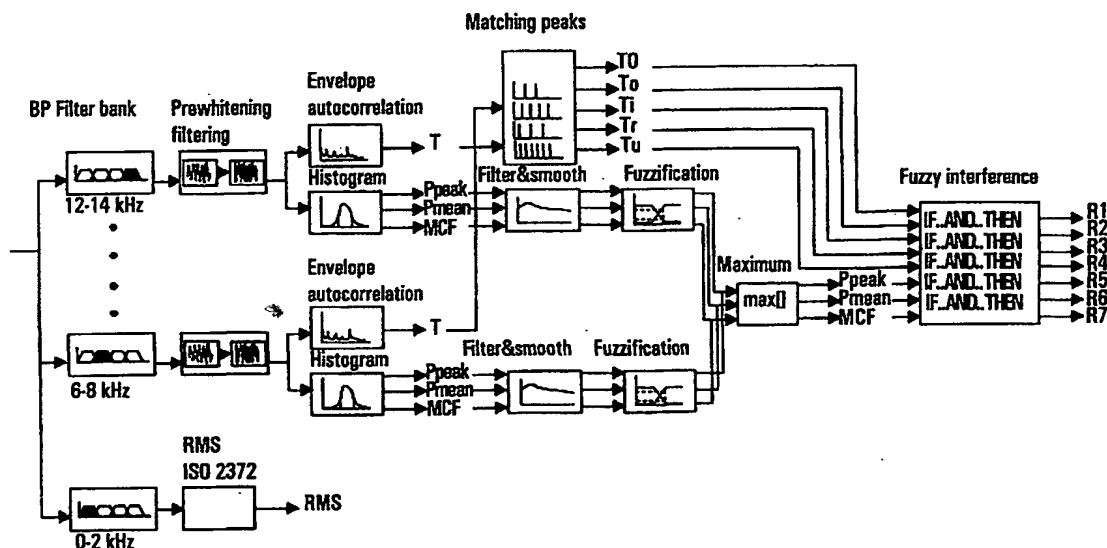


(57) Abstract

     Method of evaluating condition of a bearing component and an arrangement for the same are disclosed. The method comprises steps of generating an analog acceleration signal indicative of vibration in the bearing component and subsequent A/D converting of the analog acceleration signal to a digital acceleration signal. The acceleration signal is sampled so as to locate parts of the acceleration signal resulting from a bearing fault. Predetermined features which are determined as sensitive to bearing faults are extracted from the sampled acceleration signal, and possibilities for different fault types are computed on the basis of the extracted features and rules included in a knowledge base. An overall condition estimate is determined on the basis of the computed possibilities for different fault types.

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# BEARING CONDITION EVALUATION

## Field of the invention

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The invention relates to a method of evaluating or monitoring and analyzing the condition of a bearing or bearings enabling a relative movement e.g. between two members of a machine. The present invention relates also to an arrangement for
10 condition evaluating of a bearing or bearings.

## Background of the invention

Various kinds of machines and apparatus including a rotary or
15 linear or other type of relative movement between two members of the apparatus are in use in different fields of industry. These include electric motors and generators, gear boxes, rotatable roll apparatus, different kinds of actuators etc. From these the electric machines, such as induction motors
20 operating with a constant speed, are considered as the prime workhorse of today's industry. According to recent surveys, bearing faults of the electric machines are the most common cause of production disturbances and unexpected plant downtime resulting from a machine failure (bearing faults
25 correspond to 50-55% of all machine failures, followed by various electrical faults).

In order to avoid unexpected machine breakages it is impor-tant to be able to constantly and in a reliable manner
30 evaluate and predict the condition of the bearings of a ma-chine. The predictive and preventive condition monitoring of e.g. rolling element bearings (rolling bearings) and electri-cal machines by using a vibration measurement and/or shock pulse measurement (SPM) is therefore researched actively and
35 several methods of analyzing the vibration and/or shock pulses have been suggested and also applied.

The currently used bearing condition monitoring methods typically compare the spectrum of a vibration measurement or an envelope thereof to a reference result obtained for a

5  machine which is working properly, i.e. does not contain damaged bearings or any other damaged components. In most cases this comparing is done by a skilled and trained expert. At present in a typical commercially available vibration monitoring solution, one normally compares power spectral

10  density (PSD) estimates of the vibration signal or PSD estimates of the envelope of the vibration signal to a 'fingerprint PSD' of the same motor in healthy condition. In a usual approach signal powers in selected narrow frequency windows are compared to alarm levels defined by the user.

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In addition to the components of the vibration spectrum, occurrences, periods and amplitudes of shock pulse measurements with specific shock pulse (SPM) sensors are also utilized as parameters which are then analyzed and from which

20  pulses a possible damage or fault of the bearing can be determined.

Self-adjusting and learning vibration monitoring systems have also been demonstrated. Many of these systems are based on

25  nonlinear modeling using artificial neural networks (ANN) or neuro-fuzzy systems (NFS). Typically, the system needs a learning period to estimate its internal parameters to fit to the normal vibration modes in a wide range of operating points (varying load, on-off duty cycle, etc.). After the

30  learning period a knowledge base for different faults has been created. The system can detect a vibration that deviates from the identified normal operation, and compare that to the information contained in the knowledge base. When a new type of abnormality is detected, an information thereof can be

35  added to the system knowledge base to be able to classify similar fault symptoms in the future.

However, there are still some fundamental problems in the area of bearing condition evaluation. In general it can be said that the present vibration analyses require considerable amounts of work by dedicated experts for obtaining reliable and understandable results. And still it has been difficult to deliver reliable estimates considering the true need for maintenance and/or repair by means of the present arrangements. In most cases the end-users of the condition monitoring products are not interested to receive "too early" fault indications - a maintenance recommendation is desired only for those machines or bearings which will not operate safely over that production period which comes after the next planned production break. Unnecessary and/or too early accomplished replacements or repairs of bearings can cause significant costs and a remarkable amount of unnecessary work and down-time of the machinery.

Main problem of the above described self-adjusting systems is the lacking a priori information of faults: an occurred fault is needed from each fault type in every installation before the fault type can be identified. Faults of a new type can at most be detected, but their type or severity can not be classified. Because of this, also the estimation of actual fault severity and maintenance need is impossible. In addition, the assumption is, naturally, that the machine was undamaged and in a proper working condition during the learning period. This is not always the case in practice, e.g. due manufacturing faults in the components of the machinery and/or incorrect assembly work.

**Summary of the invention**

It is an object of the present invention to overcome the disadvantages of the prior art solutions and to provide a new type of solution for evaluating bearing condition.

An object of the present invention is to provide an evalua-
tion method and arrangement which provide an automatically
operating evaluation system.

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An object of the present invention is to provide a method and
arrangement by means of which the initialization procedure of
an evaluation system is eased, made faster and automatized.

10   An object of the present invention is to provide a method and
an arrangement by means of which the severity of the bearing
fault can be estimated.

An object of the present invention is to provide a evaluation
15   method and arrangement which provides clear and understan-
dable evaluation results on basis of measurement of the
acceleration of the vibration.

Other objects and advantages of the present invention will be
20   brought out in the following part of the specification taken
in conjunction with the accompanying drawings.

The objects are obtained by a method of evaluating condition
of a bearing component. The method comprises steps of genera-
25   ting an analog acceleration signal indicative of vibration in
the bearing component, A/D converting the analog acceleration
signal to a digital acceleration signal, sampling the digital
acceleration signal so as to locate parts of the digital
acceleration signal resulting from a bearing fault,
30   extracting predetermined features determined as sensitive to
bearing faults from the sampled digital acceleration signal,
computing possibilities for different fault types on basis of
the extracted features and rules included in a knowledge
base, and determining an overall condition estimate of the
35   fault severity on basis of the computed possibilities for
different fault types.

Arrangement for evaluating condition of a bearing component comprises means for detecting and generating an acceleration signal indicative of vibration in the bearing component, converter means for converting the acceleration signal to a digital acceleration signal, processing means arranged to sample the digital acceleration signal so as to locate parts of the digital acceleration signal resulting from a bearing fault, processing means arranged to extract predetermined features sensitive to bearing faults from the sampled digital acceleration signal, a knowledge base containing empiric information of the bearing component and rules for condition analysis, processing means arranged to compute possibilities for different fault types on basis of the extracted features and the information from the knowledge base, processing means arranged to form an overall condition estimate of the fault severity on basis of the computed possibilities, and means for outputting the condition estimate.

Several advantages are obtained by means of the present invention, since the solution provides a reliable, controllable and automatic manner for evaluating bearing condition. The solution provides a fully automatic analysis and no user or expertise intervention is required to obtain the results of the evaluation. E.g. the following fault types can be easily and reliably identified with the corresponding maintenance recommendations: defect on the inner or outer race of the bearing, defect in a rolling element, resonance or looseness in the bearing or evenly worn bearing. Also inadequate lubrication or impurities in the lubricative will be seen as defect on a roller or the bearing race. The solution provides the user with estimates of the severity of different fault types in the monitored bearing. Knowing the fault type, the inventive system can also justify the urgency of the maintenance need accordingly (some faults need quick actions, whereas some faults can be detected well in advance before developing to critical, and therefore the operation of the

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machinery can be continued in a normal manner or with decreased running time loading). No set-up of warning or alarm levels is required from the user side since the solution provides also automatic initialization routines. The
5 system can be initialized also for bearings that are already damaged. In addition, no separate shock pulse sensor is needed to detect shock pulses, as is the case in many of the prior art systems.

10 In the following the present invention and the other objects and advantages thereof will be described in an exemplifying manner with reference to the annexed drawings, in which similar reference characters throughout the various figures refer to similar features.

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**Brief description of the drawings**

Figure 1 is a schematic illustration of a possible monitoring arrangement for bearing condition evaluation;

20
Figure 2 discloses a flow chart for operation in accordance with the present invention;

Figure 3 is a schematic presentation of a principal frequency
25 distribution of shock pulses;

Figure 4 discloses schematically a typical envelope autocorrelation function form for a damaged bearing component;

30 Figures 5a, 5b and 5c disclose membership functions for M, $P_{peak}$ and $P_{mean}$;

Figure 6 discloses a table for fault possibilities in different fault classes;

35
Figure 7 discloses a block diagram for one embodiment; and

Figure 8 discloses an example of development of the diagnostic output versus time in one test case.

5    **Detailed description of drawings**

Figure 1 is a schematical presentation of one possible general arrangement for enabling the operation of a bearing condition monitoring system. The machine 1 to be monitored
10   can be e.g. an electric induction motor, a shaft 4 thereof being arranged to operate with an essentially constant or nearly constant speed. The operation of the motor 1 is controlled by a control unit / power supply 2 via a connection 3. An electric machine, and the operation and various possi-
15   bilities for power supply and control thereof are per se known to a skilled person, and are thus not explained in more detail herein. It is sufficient to note that to enable the operation of an electric motor, some kind of support bearing arrangement is required for the rotating shaft 4 thereof to
20   enable as frictionless rotation as possible of the shaft.

Figure 1 discloses schematically a rolling bearing component 5 rotatably supporting the shaft 4. The inner race 5i and the outer race 5o of the bearing component 5 are also shown. Even
25   though not disclosed, it is to be understood that in a usual case bearings are provided in both ends of the motor and that there are several different ways to accomplish the rotatable support by bearings for a machine. The way how the bearings are arranged between the various members of the machine,
30   however, is not a part of the invention, and the different alternatives for the bearings are thus not discussed in more detail herein.

An acceleration detector or accelerometer 10 capable of pro-
35   ducing an acceleration signal on basis of an acceleration measurement is mounted to the bearing 5 so as to detect the possible shocks or similar events in the bearing 5. It is to

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be noted that the detector 10 does not need to be directly attached on the surface of the bearing component, but that it is enough to position the detector relative to the bearing such that the detector is capable of detecting any such events in the bearing component which are determined to have a meaning when monitoring the working conditions of the bearing component.

As is known in the art, a common acceleration detector or an accelerometer transforms mechanical motion into an analogue signal proportional to the vibration acceleration of the system under detection. Most accelerometers use piezoelectric materials as a major sensing component of the transducer. The piezoelectric material forms electrical voltage proportional to the force as the atoms within the material are displaced. The produced voltage is very low and it is usually amplified with a charge amplifier to produce amplified voltage signal proportional to the acceleration. The sensitivity of an accelerometer and a charge amplifier is typically in the order of 50 - 100 mV/g.

The detector 10 is connected by an operational connection, such as e.g. a connector line 11 or radio or infrared connection, to a processing means 12 of the monitoring system. The processing means can be a data processing device comprising a central processing unit CPU (e.g. a microprocessor) and necessary memory arrangements (such as ROM and RAM) and necessary interfaces towards other apparatus included in the system. According to one embodiment the data processing device 12 comprises a personal computer (PC). The function of the processing means 12 is to accomplish the necessary evaluating operations and computations after having received the acceleration signal, as will be explained later on in this description, and therefore any apparatus providing the necessary functionality for accomplishing the required data processing and computations can be utilised in this.

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It is noted that the arrangement may also be arranged to use separate processing means for the different proceedings and tasks instead of one central data processing unit. In addi-
5   tion, a part of the required processing means may comprise e.g. microprocessors and a software implemented therein, while a part of the processing means of the same arrangement may comprise special circuitry and logical units arranged to proceed a predefined part of the functionality.

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The processor unit 12 may comprise various databases for analysing, monitoring and/or controlling purposes. An impor-tant database is a specific knowledge base 20 and/or rule base containing rules for the evaluation. These rules for the
15  various stages of evaluation, such as stages for pre-processing and processing of an acceleration signal, analysis and estimations, will be explained in more detail later in this description.

20  Heuristic and empiric knowledge concerning the bearing(s) and/or machine under surveillance may also be stored in the same knowledge base 30. According to an alternative another knowledge base can be provided for the heuristic and/or em-piric information. The heuristic knowledge can be defined as
25  a linguistic description which relates or associates values or changes in some of the measured quantities or features extracted from the measurements or a combination of such values and/or changes to predefined bearing condition classes. This information may, for example, be empirical
30  knowledge from test results, theoretically derived physical knowledge, or expert knowledge by an experienced person.

It is noted that the necessary empirical knowledge is prefe-rably included in the system. More precisely, the knowledge
35  can be presented as rules in the diagnostic rule base.

In addition, the processing unit 12 may comprise a data base
for mean value data collected during the automatic initiali-
sation routine when the monitoring apparatus is started for
the first time, e.g. during a start-up of an entirely new
5    apparatus.

The data in the knowledge bases can be updated. The update
data can be either obtained from the machine monitored by the
particular processing unit, or the update data can be
10   imported through a suitable interface. The processing unit
may interface and communicate towards another data processing
device or similar through a suitable bus or a local area
network (LAN) or a direct connection between the processing
unit 20 and another data processing device, e.g. via a serial
15   port of the data processing device. Various alternatives for
the communications between data processing devices are per se
known, and are thus not explained in more detail herein.

A feed-back connection 15 is arranged between the processing
20   unit 12 and the control or power supply unit 2 of the
electric machine 1. This connection enables a direct and
automatic control of the machine 1 in case of a bearing
failure, e.g. an emergency shut down of the machine 1.

25   In addition, the exemplifying system includes a display 14
for displaying the results of the analysis, either continu-
ously, periodically or on request. The display can be
replaced or accompanied e.g. by a printer or similar output
device. There may also be some other additional outputting
30   apparatus connected to the unit 12 for informing the opera-
tors from various events in the machinery. These include
alarming apparatus such as lights and buzzers or similar ap-
paratus capable of giving a clear and noticeable signal when
needed, and other user interface apparatus such as cordless
35   alarm / display devices and means enabling the system to in-
form the operators e.g. by means of voice messages.

A flow chart illustrating one possible solution for operation of the evaluation arrangement is presented in figure 2. Figure 7, in turn, shows a block diagram for the possible embodiment, disclosing the operational steps in more detail.

As disclosed by figure 2, an acceleration signal is firstly detected / measured from the bearing under observation at step 100. At a following step 102 the signal is sampled and subsequently preprocessed so as to extract features which are sensitive to bearing faults from the acceleration signal measurement. At this stage the signal has been A/D-converted for the sampling and processing purposes, in case the signal originally was in an analogue form. It is also possible to apply a prewhitening filtering to the signal at this stage.

At step 104 the processing of the extracted features is continued e.g. by removing the effects of any disturbances, e.g. such as detected motor stops and resonances etc., from the computed features. An averaging may also be applied to remove noise from the motor condition estimates output. The analysis is then accomplished at step 106 in a diagnostic part, and this is utilised to convert the combination of feature values to estimates of fault possibilities for each fault class. Finally, an overall condition estimate and a maintenance need estimate are computed at step 108, and the results of these are outputted and/or utilised in the overall control of the motor and the entire apparatus at step 110.

In the disclosed solution there is no need for a shock pulse measurement, but it is enough to have an acceleration measurement only. When analysing the bearing condition the system utilises a physical model of bearing vibration and parametric models of random processes for detecting failure sensitive features from the vibration. Based on these features it is possible to count and determine how well the measured vibration signal corresponds the theoretical ap-

pearance of the different fault types in the signal. In principle there may exist a huge amount of different fault types, but for reasons of simplicity, these can be classified into predefined number of different fault classes (one class
5   for certain types of faults). Since the severity of different fault types or classes and the required maintenance for each of the fault types or classes is known, it is also possible to establish an overall estimate for the need of maintenance or repair on basis of the detected fault class or several
10  classes. For the most fault classes the parameters under consideration are directly comparable to the severity of the fault or damage, whereby it is possible to detect the fault without any reference measurement to a machine in a healthy or undamaged condition.

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In addition, an automatic initialisation routine is provided which takes automatically into account faults which have been already detected when setting the alarming levels (threshold values for various alarms) during the initialisation
20  procedure.

A possible operation and advantages of the solution will now be described in more detail from step to step. However, as the acceleration detection and measurement (step 100) by
25  means of e.g. an acceleration detector is a well known operation in the art, it is not described in more detail, but the starting point will be the feature extraction (step 102 in figure 2). When explaining this, a reference is made also to figure 3 presenting a principal form for a power spectral
30  density of a shock pulse produced by a contact between a defected rolling element bearing race and a rolling element.

The shock pulse produced by a fault is wide-bandwidth, and therefore it is not possible to present it well and precisely
35  by a summation of sinusoidal frequency components, as is done in many of the prior art arrangements. This is one of the main reasons why the analysis of bearing faults using prior

art methods based on frequency spectrum interpretation are complex, and why there is a requirement to use dedicated experts in the evaluation process.

5   The herein disclosed feature extraction detects the transient form of the vibration shock pulse instead of the frequency spectrum as is the case in the prior art. The feature extraction utilises the fact that shock pulses produced by bearing faults are not periodical or sinusoidal by nature. 10  These are not inherently suitable for analysis using Fourier spectral analysis techniques used in the majority of the prior art systems.

The following scheme can be used in the feature extraction:
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1. Sample the acceleration signal with an adequately high sampling frequency ($f_s$). The interesting parts of the signal lay typically in the frequency range 6-20 kHz. The sampling frequency must be at least twice as high as is 20    the highest frequency of the analysed signal component. Selecting 32 kHz sampling frequency allows to analyse the frequency to up to 14 kHz and results in reduced computational effort at the later stages in the evaluation algorithm.

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2. Divide the signal to several frequency bands in the frequency range of interest (see fig. 7, in which two of the several bands are disclosed). This helps to find those signal parts that result from bearing faults by focusing 30    on the shock pulse frequency range depicted in figure 3. Using several frequency bands is advantageous since the exact location of the shock pulse components is not known in advance. The signal of interest may be present in some or all frequency bands in the case of a bearing fault. 35    Division of the signal to frequency bands that multiply to the sampling frequency by a power of two results in attractive computational reductions and an effective

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implementation. This clarifies the selection $f_s=32$ kHz: division to the frequency bands 6-8, 8-10, 10-12 and 12-14 kHz as is disclosed by figure 7 can be implemented very effectively. However, also other selections for $f_s$ are possible to obtain the same functionality.

3. Remove the influence of any deterministic signal components by supplementing the extraction with prewhitening filtering in each of the frequency bands. For the details of the theory of prewhitening, see e.g. Marple, S.L. Jr: "Digital spectral analysis with applications", Prentice Hall, Englewood Cliffs, NJ. USA 1987, which is incorporated herein by reference. The prewhitening filtering is used to effectively remove sinusoidal signal parts. A feature of the prewhitening filtering is that it is not sensitive to shock pulses. The resulting signal consists essentially of white noise and shock pulses only. Any prewhitening filtering method (or a prediction error filter coefficient estimation method, or a reflection coefficient estimation method, or an autoregressive (AR) - model parameter estimation method, which all produce a prewhitened signal), can be utilised. The so called Burg algorithm has been selected in this example since it is computationally effective and has shown to be numerically stable.

It is preferred to use the prewhitening when implementing the disclosed system. In view of the importance of the prewhitening it is noted that in case the prewhitening has not been performed, it can be shown that the autocorrelation of the signal envelope will have fluctuations when deterministic signals are present. These fluctuations, if present, would be misinterpreted as peaks resulting from a fault, and might thus in worst case lead into a false fault alarm.

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It is, however, noted that also other methods than pre-whitening can be used to remove the deterministic compo-nents from the signal. One possibility is to remove de-termistic peaks from the signal FFT (indicated by low ra-tion of variance and amplitude of the spectral estimate), followed by a removal of deterministic peaks and a subse-quent inverse FFT (Fast Fourier Transform). However, this may introduce some more variance into the resulting sig-nal. An ordinary Fourier Transform can also be used instead of the FFT.

4. After the preferred filtering operations, extract features that are sensitive to bearing faults. The following features can be used in the processing unit for computa-tions in each frequency band for the prewhitened signal (it is to be noted that this signal is no longer the same as the measured acceleration signal, as it has passed the above filtering operations):

a) In the autocorrelation sequence of the signal envelope, sharp peaks can be detected if shock pulses appear at regular intervals. Return the time between the shock pulses as a feature, that is, return the lag value of the first sharp peak in the autocorrelation estimate of the signal envelope. A convenient means of computing the sig-nal envelope is to utilise a complex valued Hilbert transformation filter which is a standard tool for the signal processing community.

b) From the amplitude distribution of the signal, compute percentiles (P)

$$P_n = F^{-1}\left(\frac{n}{100}\right)$$

where n denotes the desired percentile and F denotes the cumulative distribution function.

Compute now $P_1$, $P_{30}$, $P_{70}$ and $P_{99}$. Return the features to receive:

$$Ppeak = P_{99} - P_1$$
$$Pmean = P_{70} - P_{30}$$
$$MCF = Ppeak/Pmean$$

From the above the feature a) (or T in figure 7) is sensitive to shock pulses with regular intervals, Ppeak describes roughly the peak-to-peak amplitude of the signal, Pmean is proportional to the mean amplitude without the shock pulses and MCF describes the peak content of the signal.

The number and nature of the extracted features can be defined differently for different kinds of machines and/or bearings and/or applications. A possible approach might be to extract about 20 features which is considered to give reliable results in most of the applications.

In the subsequent processing and combining of the extracted features into bearing condition information the features could be combined directly to motor condition estimates by a method described later on in this description when explaining the diagnostics of the computations. However, this may lead to noisy condition estimates. To avoid this the following further processing before the actual analysis is applied to the input signals in each frequency band:

1. Convert the peak times (in seconds) to indicators describing recent match to each fault type. This procedure will be explained in more detail later on in this description.

2. Filter the features using a digital low-pass filter with the following checks:

2a:    If Ppeak is very low, motor is not running. In this case, return the old filter output value (computed when the motor was running) until vibration levels indicate that the motor has been restarted. A simple limit or threshold value check can be used for this.

2b:    If MCF > MCF_limit occurs in some frequency band, use the old filter output values for Ppeak and Pmean in that frequency band until MCF returns to a normal range again. MCF_limit value 5.25 can be selected for most applications to indicate increase (theoretical MCF for the Gaussian noise is approximately 4.4).

"Cutting" the Ppeak and Pmean by this way helps to resolve an evenly worn bearing from vibration bursts caused by resonances or looseness in the bearing. It is also essential for an automatic initialisation run, as will be described later in this specification, where the separation of the resonance bursts from an increased overall vibration level is necessary.

The processing of the fault time peaks already referred to will now be explained in more detail with reference to figure 4.

It is characteristic for each bearing component fault or lubrication related fault that they typically produce shock pulses into the vibration signal. As already proposed by the prior art, the interval between these pulses, the pulse interval, can be computed as an inverse of the so-called pulse frequency from the bearing geometry.

The pulse frequencies are, however, used in the disclosed solution only for computing the pulse interval. Furthermore, the surprising observation here is that the peaks in the autocorrelation of the signal envelope appear in different

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locations depending on the fault severity. Small and de-
veloping faults can be seen first close to the rotation pe-
riod T_rpm of the bearing component because the shock pulse
train will be modulated with the rotating frequency.

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As the fault gets more severe (or increases), clear peaks can
be detected closer to the fundamental pulse interval. It is
possible to use different weighting for e.g. three classes of
narrow autocorrelation peaks:

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Class 1: Most severe: detected peak time is close to the
          fundamental pulse interval within a time tolerance.

Class 2: Least severe: detected peak time matches (within a
15        certain time tolerance) the multiple of the pulse
          interval which is the closest to the rotating pe-
          riod.

Class 3: Medium severity: detected peak time matches some
20        other multiple of the pulse interval.

The fault severity is computed for each of the bearing com-
ponent fault classes. Five new features result after fil-
tering, all having a value between 0 and 1:

25

        To    Recent pulses match outer race fault
        Ti    Recent pulses match inner race fault
        Tr    Recent pulses match rolling element fault
        Tu    Recent pulses do not match any known fault
30      T0    No shock pulses have been detected

The filtering is performed by allowing these values to move
slowly to the direction of the weighted severity of detected
pulse interval. If no shock pulses (which indicate the exis-
35 tence of a fault or several faults) have been detected, T0
will be increased and other values decreased.

Here all frequency bands are investigated to produce one set of the parameters (To, Ti, Tr, Tu, T0). Thus, if a shock pulse has the same influence to the result, it does not matter in what frequency band it has been detected. Recalling the discussion above about the wideband nature of the shock pulse spectrum, this is a natural interpretation.

When accomplishing the diagnostics, the condition analysis in the proposed method consists of two phases:

1. Compute the possibilities of different fault types, and
2. form an overall condition estimate of the fault severity.

When computing of the possibilities of different faults the vibration analysis is completed by utilising a heuristic expert knowledge on the exact features computed earlier. An appropriate framework for implementing the heuristic knowledge with a computer algorithm is utilisation of so called fuzzy logic and fuzzy reasoning.

The use of so called fuzzy sets provides a basis for a systematic way for the manipulation of vague and imprecise concepts. In particular, the fuzzy sets can be employed to present linguistic variables and fuzzy logic can be used to transform a linguistic description of diagnostic rules to a computer algorithm.

Fuzzy logic can be defined as an extension of an ordinary, boolean logic. In fuzzy logic, the concepts 'true' and 'false' are extended to denote the "degree" of the truth. Membership functions relate a crisp variable value to a degree of membership in a fuzzy set. Equivalents to the logical operations AND, OR and NOT in the boolean algebra are also defined in the fuzzy set theory. This makes it possible to analyse mathematically a set of linguistic descriptions of rules which typically are in the form:

*if* (a set of conditions is true) *then* (a set of conse-
quences can be inferred).

5    It is noted again that 'true' here means the degree of mem-
bership in the corresponding fuzzy set within the interval
[0,1]. Also the consequence part or the results are given as
degrees of membership in the corresponding fuzzy sets.

10   Now, when utilising fuzzy logic, linguistic variables defined
by fuzzy sets can be combined to produce rules for linguistic
output, i.e. for an output which is in the form of an
understandable writing. For example, the following linguistic
variables may be used:

15

        T0 =    "No shock pulses have been detected"
        To =    "Recent pulses match outer race fault"
        Ti =    "Recent pulses match inner race fault"
        Tr =    "Recent pulses match rolling element fault"
20      Tu =    "Recent pulses do not match any known fault"
        M  =    "MCF value has increased"
        Ppeak =    "Ppeak value has increased"
        Pmean =    "Pmean value has increased"

25   It is already described in above how T0, To, Ti, Tr and Tu
values are computed. These values can be interpreted as the
degrees of the membership or relation to the corresponding
linguistic sets. For M, Ppeak and Pmean, a standard fuzzifi-
cation is used with trapezoidal membership functions as shown
30   in figures 5a - 5c. Trapezoidal fuzzy sets are a suitable
selection since all of the features increase proportionally
to the fault severity.

The values M_lo = 5 and M_hi = 10 have been selected here on
35   the basis of the theoretical value 4.4 for Gaussian noise
(the normal bearing vibration in high frequencies after a
prewhitening is typically Gaussian). MCF values up to 25 have

been measured in field tests for very severe bearing fault
types.

Mpeak_lo, Mpeak_hi, Mmean_lo and Mmean_hi are determined
automatically during the initialisation run separately for
each of the frequency bands.

The linguistic variables for the output may be for instance
(in figure 7, these are denoted by R1, R2, .... R7, respec-
tively):

        OK  = "Vibration is OK"
        Fo  = "Fault on the outer race of the bearing"
        Fi  = "Fault on the inner race of the bearing"
        Fr  = "Fault on a rolling element of the bearing"
        R   = "Resonance or looseness"
        W   = "Evenly worn bearing components"
        U   = "Unknown fault"

The following (narrow) rules can be used to determine the
condition of the bearing so as to produce the above results:

        1.)  IF (Pmean OR Ppeak) AND NOT M THEN W
        2.)  IF M AND T0 THEN R
        3.)  IF T0 AND NOT M AND NOT Pmean AND NOT Ppeak THEN OK
        4.)  IF Tu AND m THEN U
        5.)  IF M AND To THEN Fo
        6.)  IF M AND Ti THEN Fi
        7.)  IF M AND Tr THEN Fr

The possibilities of the fault classes are determined simply
by computing the rule output using fuzzy inference methods
described e.g. in the literature of the art. The output gives
membership value (the possibility) of each fault class
between 0 and 1.

From the above rules the rule number 1.) is fully active only
when the initialisation routine has been successfully passed
in one frequency band. Most of the bearing faults can be
found also using the other rules, in which case the bearing
5    protection system is active immediately.

Fault classes Fo and Fi indicate also inadequate lubrication
(metal contact through the lubricating oil film) or impuri-
ties in the lubricative (small particles causing shock
10   pulses).

The overall condition estimate, in turn, can be given by a
simple limit check for the fault class possibilities. Overall
status can be indicated for example by means of colour
15   indicators: green, yellow, red. From these, green colour
indicates a proper working condition, yellow a slightly
damaged or less severe condition and red a severe damage.

Different limit values (between 0 and 1) for each fault can
20   be used when computing the overall condition estimate from
the fault possibilities. This way the normal looseness in
certain bearing types can be tolerated without a warning or
an alarm. It is also possible to react more promptly to an
inner race fault, since it will be seen not as clearly as the
25   outer race faults in the vibration signal. Different set-ups
for overall alarm sensitivity can also be used according to
requirements set by the user (for very critical applications,
an earlier warning is desirable). After an alarm, the user
can check the cause directly from the possibilities of the
30   condition classes. Figure 6 discloses one example for a fault
possibility table stored in the knowledge database of the
processing means of the evaluation arrangement.

One important feature which is enabled by the solution is an
35   automatic initialization of the condition evaluation system.
The automatic initialization of Ppeak_lo, Ppeak_hi, Pmean_lo
and Pmean_hi is performed by computing the mean value of the

filtered Ppeak and Pmean values in all frequency bands and
setting the limits above the mean values:

$$Ppeak\_lo = 2 \times E(Ppeak)$$
$$Ppeak\_hi = 4 \times E(Ppeak)$$
$$Pmean\_lo = 2 \times E(Pmean)$$
$$Pmean\_hi = 4 \times E(Pmean)$$

wherein E denotes the mean value operation over a time
period.

The mean or average values are computed only when the
machine, such as a motor is running. A period of several days
(e.g. from 3 to 7 days) is used to compute the average level
of bearing vibration in the normal operating cycle of the
machine.

As described earlier, an increased MCF is used to detect
resonance bursts in the vibration. Measurements with a high
MCF are not used in the initialisation cycle, as it is
required that the MCF value is normal for a sufficiently long
time period during the initialisation (the requirement can be
for example that the MCF has to be below 5.25 for 20% of the
total initialization cycle). Otherwise, initialization status
"failed" will be returned for the corresponding frequency
band and these frequencies will not be used for diagnostics
with the rule 1.) described above.

Figure 8 discloses an example of the results or output of
test diagnostics. The output can be e.g. a print list on pa-
per or a display in a screen. The vertical axis of the
different curves describes the possibility for the fault in
each class in a range from 0 to 1, whereas the horizontal
axis defines the time. Each of the curves presents one fault
or condition type.

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The first curve indicates the possibility of perfectly normal vibration. A drop of the possibility from the level 1 indicates that minor declinations from normal vibration are present in the measured signal (OK). The second curve is for
5      the outer race faults (Fo), and can be seen to indicate that the bearing is likely to have a fault in the outer bearing race. Similarly, the third (inner race) curve (Fi) and fourth (rolling elements) curve (Fr) show the possibilities of these fault types. Fifth curve (R) indicates the possibility of
10     resonance or looseness in the bearing. Sixth curve (W) indicates even wear of the bearing, the possibility for this being zero. The seventh curve (U) is for "unknown fault".

Thus, the invention provides a solution by which a signifi-
15     cant improvement can be achieved in the area of bearing con- dition evaluation. The arrangement according to the present invention is easy and economical to realise by per se known components and reliable in use. The disclosed system provides the user with estimates of the severity of different fault
20     types in the monitored bearing. Knowing the fault type, the system can justify the urgency of the maintenance need accordingly, since some of the detected faults need quick actions, whereas some other fault types can be detected well in advance and followed up before they are developing to
25     critical. No set-up of warning or alarm levels is required from the user. The system includes automatic initialisation routines. The system can be initialised also for bearings that are damaged. No separate shock pulse sensor is needed to detect shock pulses.

30
It should be noted that the foregoing examples of the embodi- ments of the invention are not intended to restrict the scope of the invention to the specific forms presented above but the present invention is meant rather to cover all
35     modifications, similarities and alternatives which are in- cluded in the spirit and scope of the present invention, as defined by the appended claims. All additional embodiments,

modifications and applications obvious to those skilled in the art are thus included within the spirit and scope of the invention as set forth by the claims appended hereto.

## Claims

1. Method of evaluating condition of a bearing component, comprising

generating an analog acceleration signal indicative of vibration in the bearing component;

A/D converting the analog acceleration signal to a digital acceleration signal;

sampling the digital acceleration signal so as to locate parts of the digital acceleration signal resulting from a bearing fault;

c h a r a c t e r i z e d by further comprising

extracting predetermined features determined as sensitive to bearing faults from the sampled digital acceleration signal;

computing possibilities for different fault types on basis of the extracted features and rules included in a knowledge base; and

determining an overall condition estimate of the fault severity on basis of the computed possibilities for different fault types.

2. Method according to claim 1, c h a r a c t e r i z e d in that the influence of any deterministic signal components is removed from the digital acceleration signal by means of prewhitening filtering or similar method which utilises parametric models of random signals, or by means of (Fast) Fourier Transform, removal of deterministic peaks and a subsequent inverse (Fast) Fourier Transform so as to obtain a signal consisting essentially of white noise proportional to overall smoothness of the microstructure of the bearing surface and shock pulses.

3. Method according to any of the preceding claims, c h a r a c t e r i z e d in that at least one of the following features is detected during the feature extracting

stage: sharp vibration pulses or shock pulses, peak-to-peak amplitude of the signal, a mean value proportional to the mean amplitude without shock pulses, a peak content of the signal.

4. Method according to any of the preceding claims, c h a r a c t e r i z e d in that a narrow form of shock pulses at regular intervals is detected from a narrow peak in the autocorrelation estimate of a signal envelope.

5. Method according to claim 4, c h a r a c t e r i z e d in that the location of pulse peaks in an autocorrelation estimate of a signal envelope is used when determining the fault severity.

6. Method according to any of the preceding claims, c h a r a c t e r i z e d in that the sampling occurs with a sampling frequency that is at least twice as high as the frequency of the digital signal to be sampled.

7. Method according to any of the preceding claims, c h a r a c t e r i z e d by dividing the acceleration signal into a plurality of frequency bands, wherein each of the bands is monitored separately.

8. Method according to any of the preceding claims, c h a r a c t e r i z e d in that the extracted features are processed by low-pass filtering, wherein effects of any disturbance and noise are removed from the extracted features.

9. Method according to any of the preceding claims, c h a r a c t e r i z e d in that a pulse interval is computed from the geometrical dimensions of the bearing component.

10. Method according to any of the preceding claims, c h a r a c t e r i z e d by dividing the faults into a plurality of fault types, combining the values of the extracted features with an information contained within a rule base, outputting a membership degree for each of the fault types, combining the membership degrees to form estimates of fault possibilities for each fault type.

11. Method according to any of the preceding claims, c h a r a c t e r i z e d in that in computing of the possibilities for different fault types the vibration analysis is completed by utilising heuristic knowledge, preferably by utilising fuzzy logic and fuzzy reasoning.

12. Method according to any of the preceding claims, c h a r a c t e r i z e d in that the overall condition estimate is given by using a limit check for the possibilities in the fault types or classes.

13. Method according to any of the preceding claims, c h a r a c t e r i z e d in that an automated initialisation is performed by computing a mean value for the filtered feature values in all frequency bands and by setting the membership functions of fuzzy rules based on the computed mean values.

14. Arrangement for evaluating condition of a bearing component, comprising
      means for detecting and generating an acceleration signal indicative of vibration in the bearing component;
      converter means for converting the acceleration signal to a digital acceleration signal;
      processing means arranged to sample the digital acceleration signal so as to locate parts of the digital acceleration signal resulting from a bearing fault;
      c h a r a c t e r i z e d by further comprising

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processing means arranged to extract predetermined features sensitive to bearing faults from the sampled digital acceleration signal;

a knowledge base containing empiric information of the bearing component and rules for condition analysis;

processing means arranged to compute possibilities for different fault types on basis of the extracted features and the information from the knowledge base;

processing means arranged to form an overall condition estimate of the fault severity on basis of the computed possibilities; and

means for outputting the condition estimate.

15. Arrangement according to claim 14, c h a r a c t e r i z e d by further comprising means for removing influence of any deterministic signal components from the digital acceleration signal by prewhitening filtering or similar method that utilises parametric models of random signals, or by a (Fast) Fourier Transform, subsequent removal of deterministic peaks and a subsequent inverse (Fast) Fourier Transform so as to obtain a signal consisting essentially only of white noise proportional to overall smoothness of the microstructure of the bearing surface and shock pulses.

16. Arrangement according to claim 14 or 15, c h a r a c t e r i z e d in that it further comprises filter means for low-pass filtering the extracted features to remove effects of any disturbance and noise from the extracted features.

17. Arrangement according to any of claims 14 to 16, c h a r a c t e r i z e d in that it comprises knowledge base means including heuristic knowledge which relates values or changes in at least some of the measured quantities or features extracted from the measurements or a combination of such vales or changes to various bearing condition classes.

18. Arrangement according to any of claims 14 to 17, c h a r a c t e r i z e d in that it further comprises fuzzy logic means for accomplishing fuzzy reasoning for obtaining a
5   linguistic condition estimate.

19. Arrangement according to any of claims 14 to 18, c h a r a c t e r i z e d in that it further comprises a feed-back connection arranged between the processing means
10  arranged to form the overall condition estimate and a control or power supply unit of the machine including the monitored bearing component.
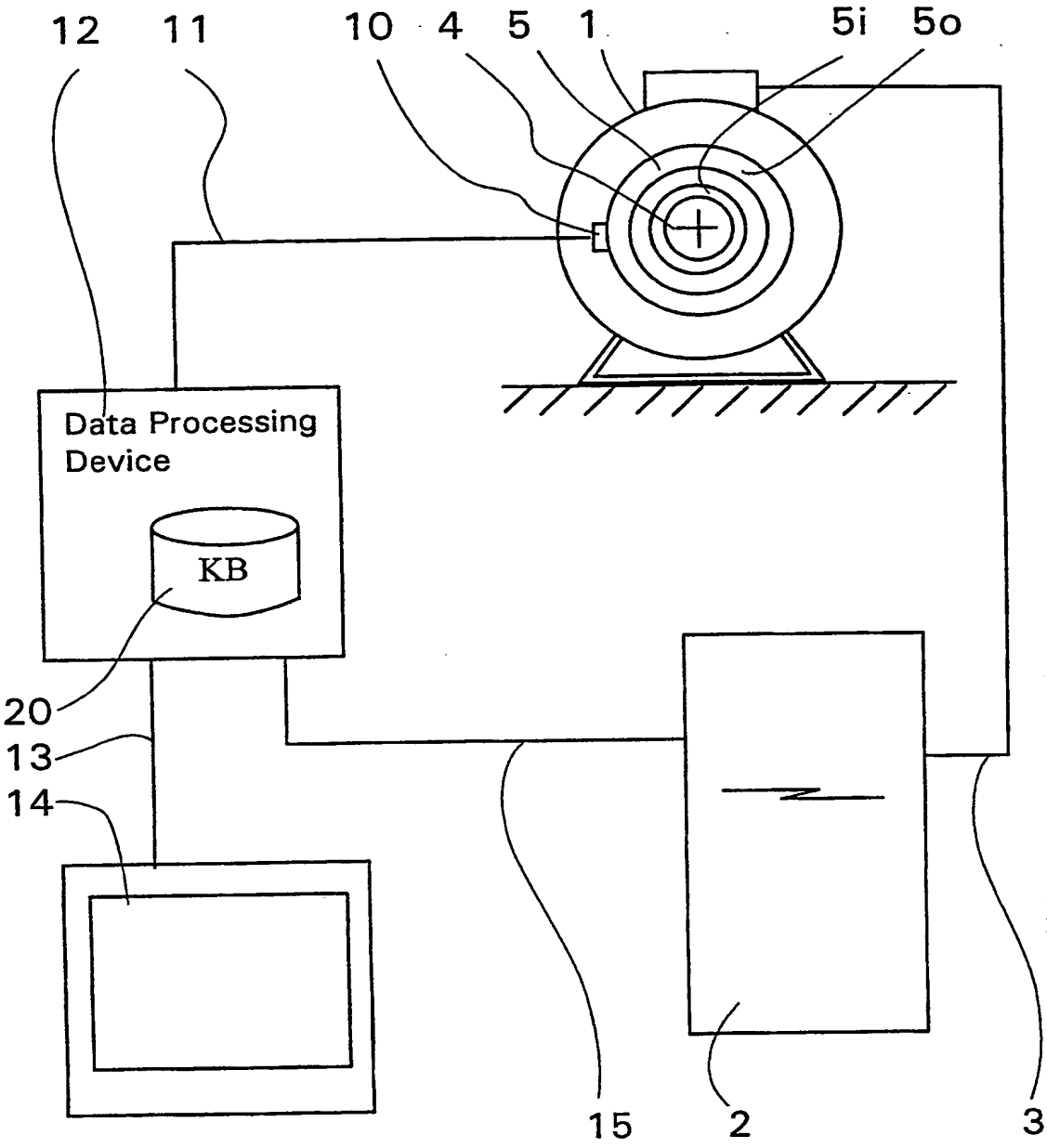
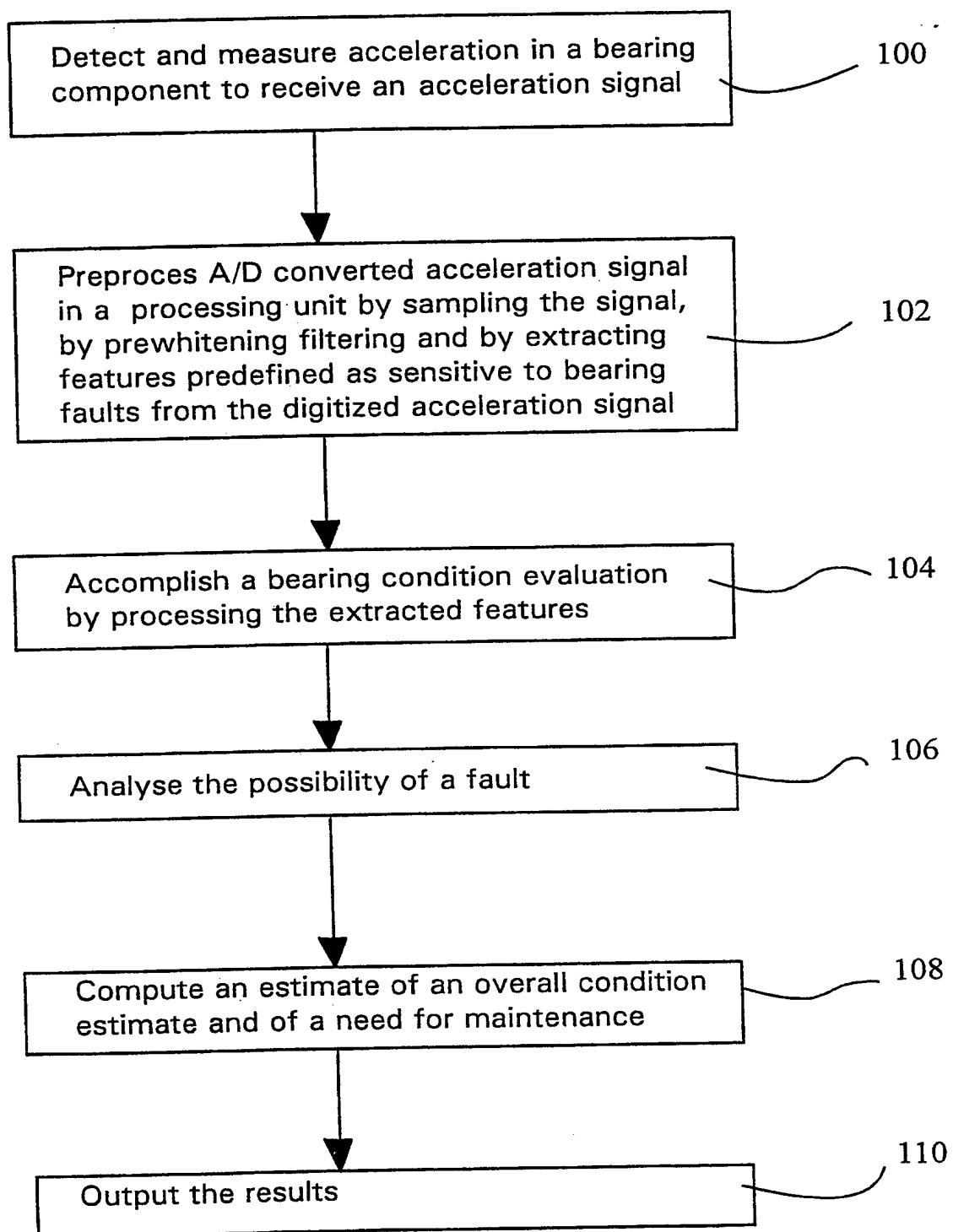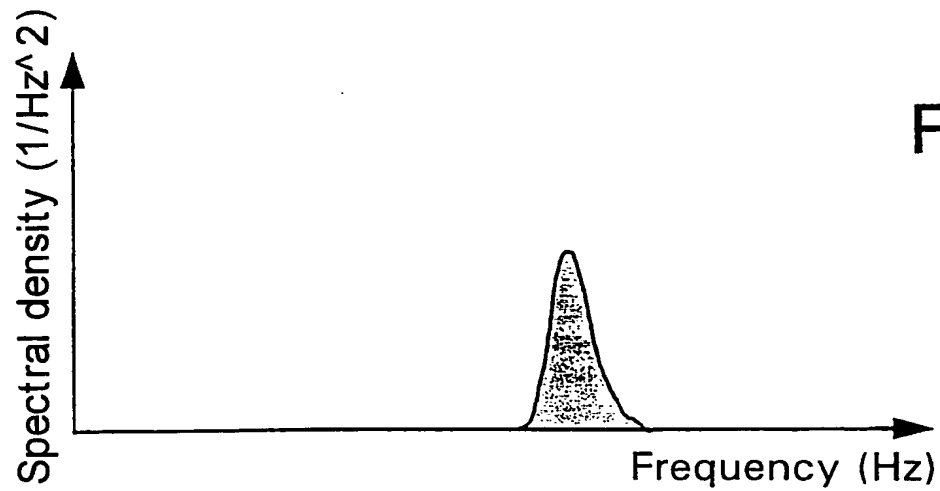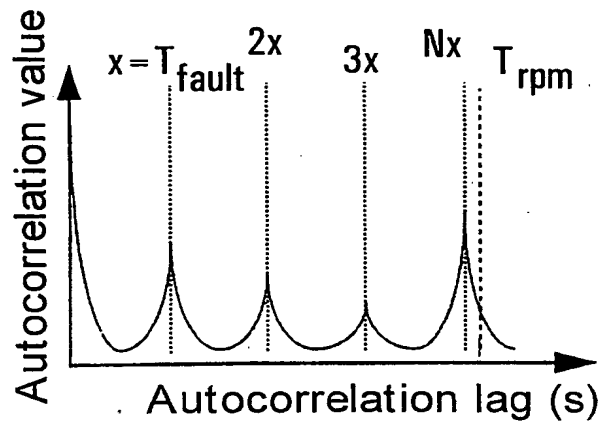12   11   10  4   5   1          5i   5o

Data Processing
Device

KB

20

13

14

15   2   3

# Fig. 1

Detect and measure acceleration in a bearing
component to receive an acceleration signal — 100

Preproces A/D converted acceleration signal
in a processing unit by sampling the signal,
by prewhitening filtering and by extracting — 102
features predefined as sensitive to bearing
faults from the digitized acceleration signal

Accomplish a bearing condition evaluation
by processing the extracted features — 104

Analyse the possibility of a fault — 106

Compute an estimate of an overall condition
estimate and of a need for maintenance — 108

Output the results — 110

## Fig. 2

Fig. 3



Fig. 4

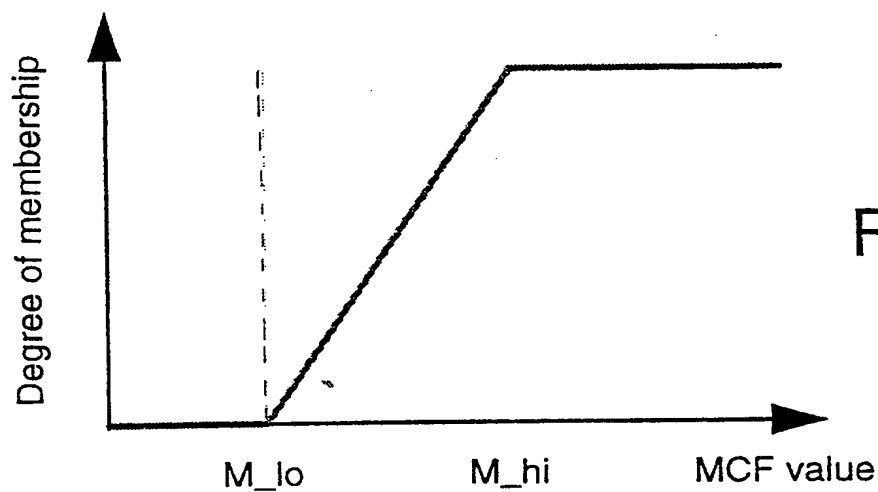| Fault class | Possibility |
|-------------|-------------|
| 1 | 15 % |
| 2 | 3% |
| 3 | 14% |
| 4 | 60% |
| 5 | 43% |
| 6 | 22% |

Fig. 6
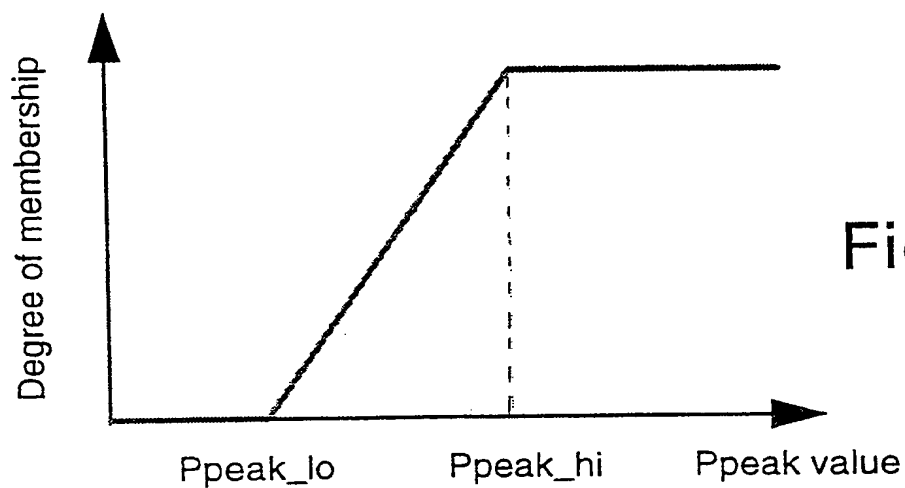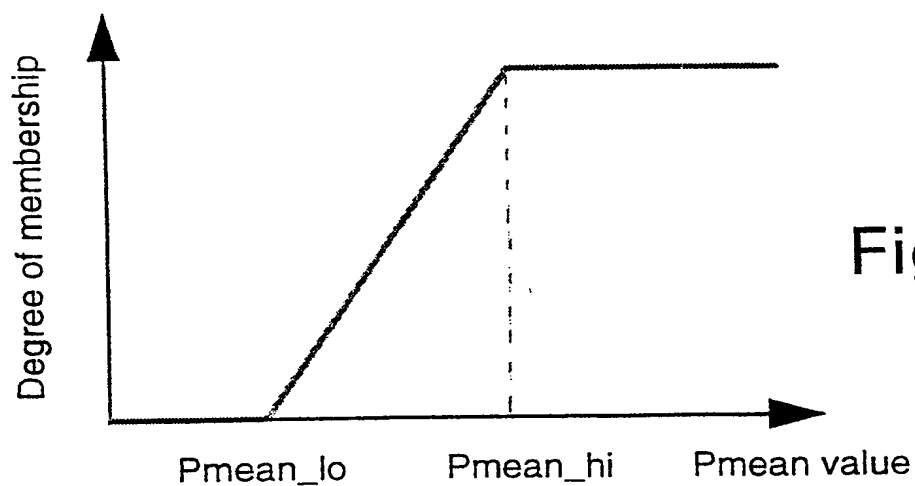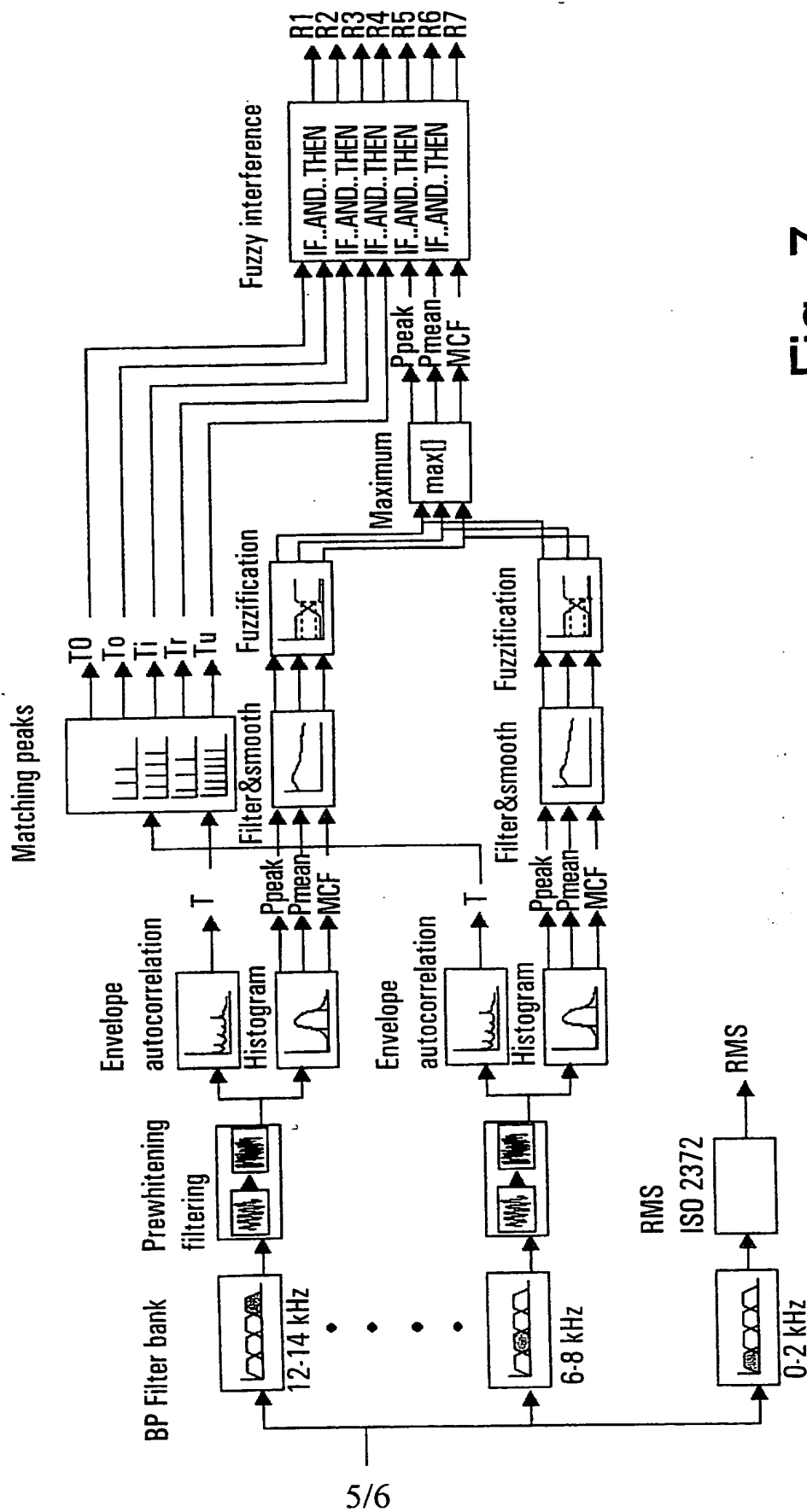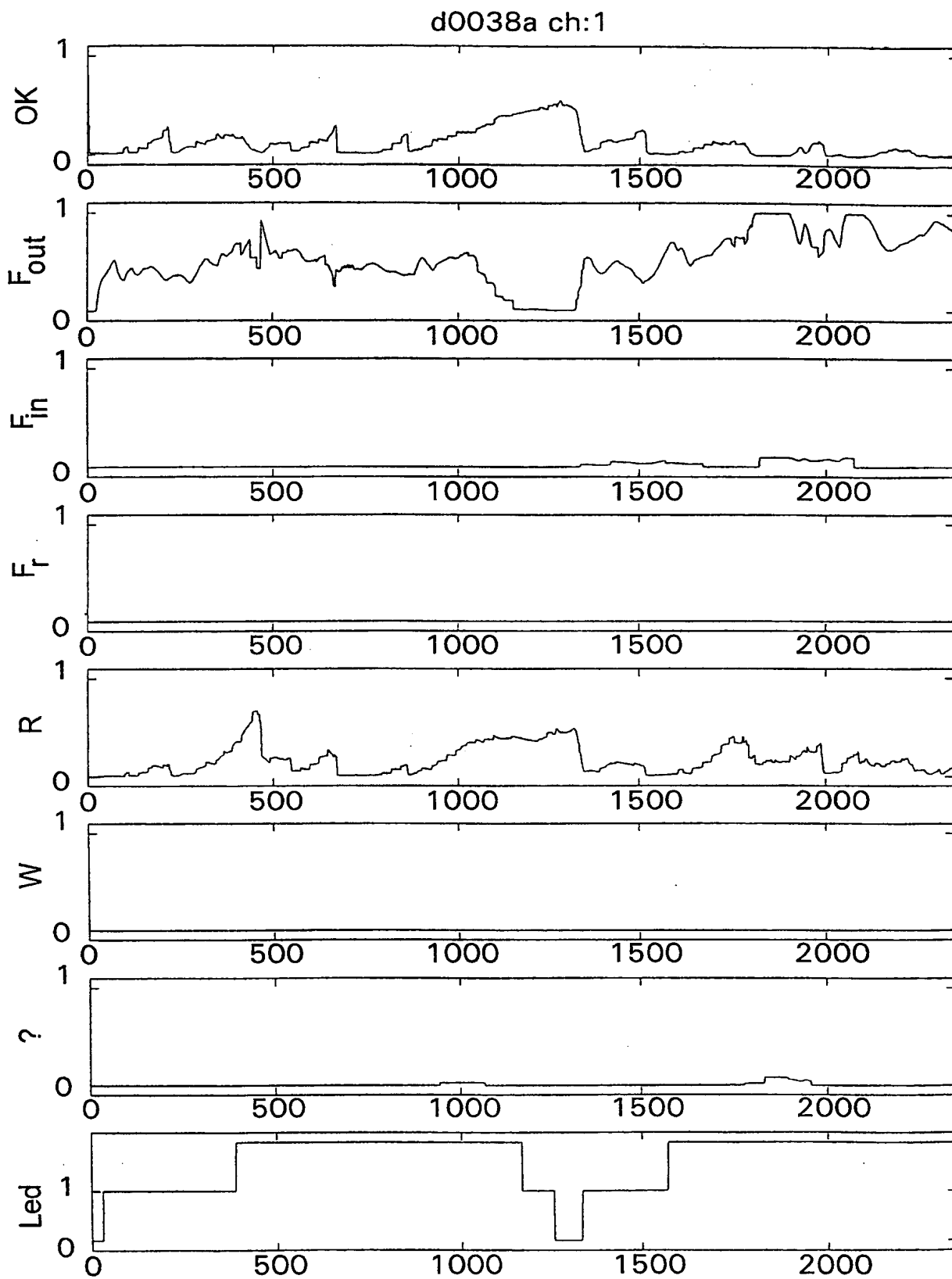
3/6

**SUBSTITUTE SHEET   (Rule 26)**

Fig. 5a



Fig. 5b



Fig. 5c

Fig. 7

SUBSTITUTE SHEET (RULE 26)

d0038a ch:1



Fig. 8

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# INTERNATIONAL SEARCH REPORT

## A. CLASSIFICATION OF SUBJECT MATTER

IPC6: G01M 13/00, G01M 13/04

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: G01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
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| X | US 5566092 A (H.WANG ET AL), 15 October 1996 (15.10.96), column 10, line 26 - column 12, line 32, figures 1-21 | 1-3,6-19 |
| A | US 4352293 A (N.KURIHARA ET AL), 5 October 1982 (05.10.82), figures 1-9, abstract | 1-19 |
| A | US 5511422 A (W.C.HERNANDEZ), 30 April 1996 (30.04.96), figure 7, abstract | 1-19 |

[X] Further documents are listed in the continuation of Box C.    [X] See patent family annex.

| * | Special categories of cited documents: | "T" | later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention |
|---|---|---|---|
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| "E" | erlier document but published on or after the international filing date | "X" | document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone |
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| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 24 November 1999 | 09 -12- 1999 |
| Name and mailing address of the ISA/ Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. + 46 8 666 02 86 | Authorized officer Lars Jakobsson/ itw Telephone No. + 46 8 782 25 00 |

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| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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| C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT | | |
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Information on patent family members

02/11/99

| Patent document cited in search report | | Publication date | Patent family member(s) | | Publication date |
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| | | | FR | 2714750 A,B | 07/07/95 |
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| US | 5726905 A | 10/03/98 | NONE | | |